Combined Cycle Power generation

Introduction

Power generation is essential to a country's commerce and industry. As the demand for power increases, more efficient power generation systems are developed. The growing environmental concern especially with regards to carbon emission also leads to emphasis on cleaner power generation systems. Combined cycle power generation is one such system that is gaining popularity among nations. Combined cycle power generation accounts for up to 49% of Singapore's power generation capacity (1).

Senoko combined cycle power plant (2).

Senoko Power has 5 combined cycle plants with output totalling 1945MW (3).

This report aims to look into the main features of the combined cycle power generation system and its relevance to energy efficiency.

1. J B X Devotta, "1. Work, Energy and Power", *GEM2501 Electric Energy - Powering the New Millenium* lecture notes, p12
2. *Siemens Power Generation*, http://www.powergeneration.siemens.com/press/press-pictures/combined-cycle-power-plants/senoko.htm (accessed February 27, 2008)
3. "Our Plant", *Senoko Power*, http://www.nwsp.com.sg/plant.asp (accessed February 27, 2008)

Main features

Combined cycle power generation combines 2 cycles for operation, namely the gas turbine cycle and the vapour power (or steam turbine) cycle.

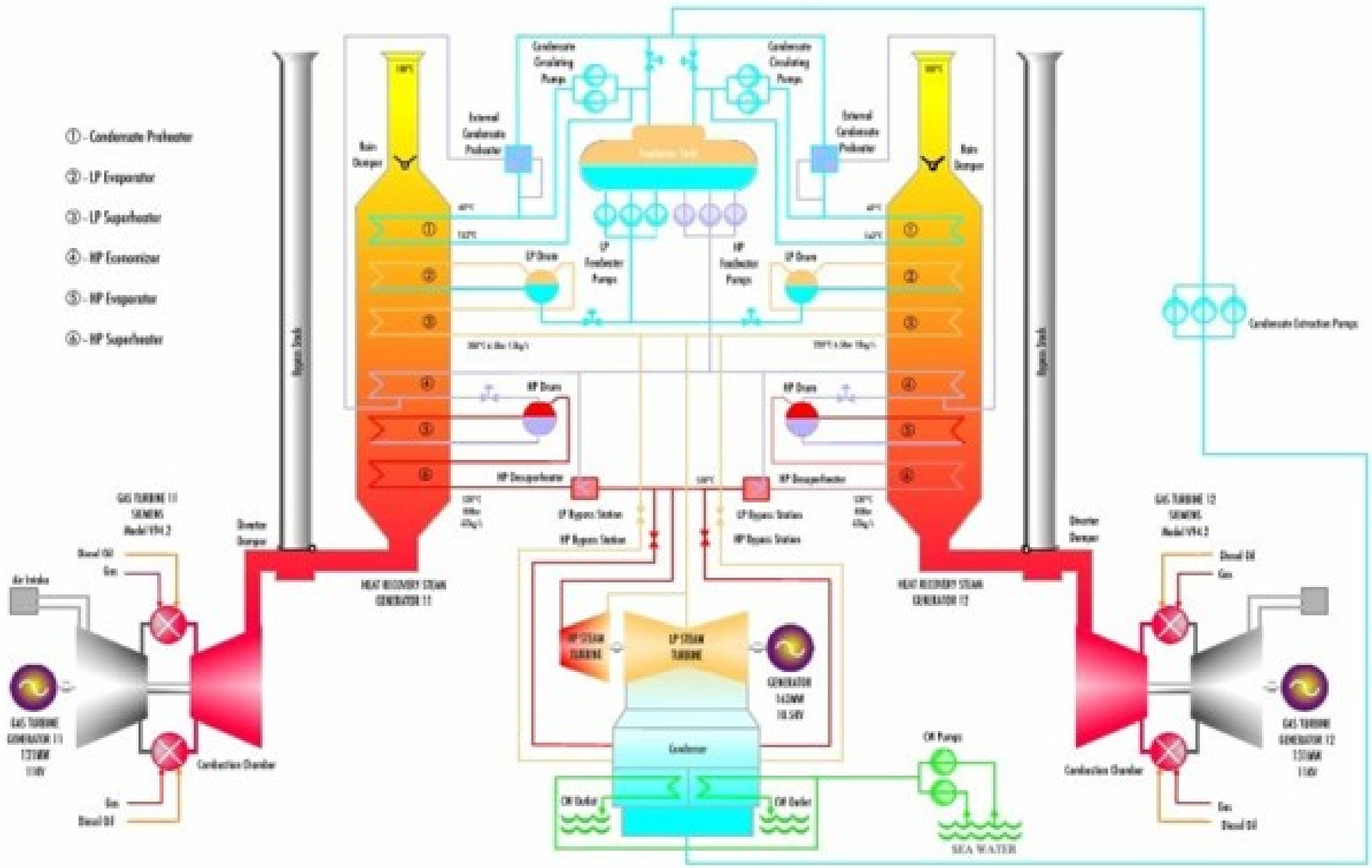
In a gas turbine power plant, natural gas and compressed air undergo combustion. The resultant high pressure gas drives the gas turbine which in turn produces electricity. Although it is clean and fast in starting up, the gas turbine power plant suffers from low thermo efficiency of about 25 to 30% (4). Much of the energy is wasted in the form of gas turbine exhaust.

The combined cycle power generation makes use of the merits of the high temperature (1100 to 1650°C) gas turbine cycle and the lower temperature (540 to 650°C) steam turbine cycle (5). The hot exhaust gas from the gas turbine, instead of being released as waste, is captured and channelled to the steam turbine where steam is heated by the exhaust to drive the turbine.

4. Everett B. Woodruff, Herbert B. Lammers and Thomas F. Lammers, “Boilers”, *Steam Plant Operation*, (McGraw Hill, 7th ed), p115
5. M.M. El-Wakil, “Gas-turbine and Combined Cycles”, *Powerplant Technology*, (McGraw Hill, 1985), p341

The diagram below shows the flow schematic of the combined cycle plant (6).

6. “Senoko Combined-Cycle Plants 1 & 2”, *Senoko Power*, http://www.nwsp.com.sg/plant.asp (accessed February 27, 2008)



Schematic Diagram Of One Block Of 425 MW Combined Cycle Power Plant

A combined cycle power plant consists of two main parts: the gas turbine plant and the steam turbine plant.

In the gas turbine plant, atmospheric air enters through the compressor and into the combustor (or combustion chamber) where fuel (usually natural gas) is added. Combustion takes place and the hot gas drives the turbine, which in turn drives the generator and produces electricity.

The hot flue gas from the gas turbine enters a heat exchanger, sometimes known as heat recovery boiler (7) or heat recovery steam generator (8), where it is used to heat up the steam. The superheated steam is then used to drive the steam turbine which in turn drives the generator to produce electricity. The exit steam from the steam turbine goes through a condenser and then back to the heat exchanger where the cycle repeats itself.

There are various types of combined cycle power generation, some of them are combined cycle with supplementary firing, combined cycle with regeneration, combined cycle with feedwater heating, combined cycle with multipressure steam cycle and combined cycle for nuclear power plants (9).

7. El-Wakil, p342
8. Woodruff and Lammers, p112
9. El-Wakil, pp342, 348, 351

Relevance to energy efficiency

Carnot efficiency is given by

$$\eta = \frac{T_H - T_C}{T_H}$$

where T_H is the temperature of the hot reservoir (ie the input gas temperature) and T_C is the temperature of the cold reservoir (ie the output gas temperature). On its own, the Carnot efficiency of a gas turbine cycle is poor as the T_C, which is the flue gas temperature, is still relatively high at about 540°C (10), thus explains its poor thermal efficiency. In the case of a combined cycle, the T_C is actually the waste heat temperature at the steam cycle's condenser which is lower than that of the gas cycle, thus a combined cycle has a higher Carnot efficiency.

The combined cycle has a better thermal efficiency compared to either of gas turbine cycle and steam turbine cycle individually. The thermal efficiency of a combined cycle is given by

$$\eta = \frac{\dot{W}_{gas} + \dot{W}_{steam}}{\dot{Q}_{in}}$$

where $\dot{W}_{gas}$ is the net power produced by the gas turbine, $\dot{W}_{steam}$ is the net power produced by the steam turbine, and $\dot{Q}_{in}$ is the rate of heat transfer to the gas turbine (11).

10. Woodruff and Lammers, p115
11. Michael J. Moran and Howard N. Shapiro, "Gas Power Systems", *Fundamentals of Engineering Thermodynamics*, (John Wiley & Sons, Inc, 2nd ed), p404

A more detailed working on the thermal efficiency of the combined cycle power generation system is given below:

Thermal efficiency of gas turbine plant:

$$\eta_{gt} = \frac{Q_{gt} - Q_{st}}{Q_{gt}} = 1 - \frac{Q_{st}}{Q_{gt}} = 1 - \frac{q_{st}}{q_{gt}}$$

$$\eta_{gt} = \frac{w_{gt}}{q_{gt}}$$

Heat supplied to the steam plant, which is also the heat exhaust from gas plant:

$$q_{st} = (1 - \eta_{gt}) q_{gt}$$

Thermal efficiency of steam turbine plant:

$$\eta_{st} = \frac{w_{st}}{q_{st}} = \frac{w_{st}}{(1 - \eta_{gt}) q_{gt}}$$

Shaft work for steam turbine:

$$w_{st} = \eta_{st} (1 - \eta_{gt}) q_{gt}$$

Thermal efficiency of combined cycle plant:

$$\eta_{gst} = \frac{w_{gt} + w_{st}}{q_{gt}}$$

$$= \frac{w_{gt}}{q_{gt}} (1 + \frac{w_{st}}{w_{gt}}) = \eta_{gt} (1 + \frac{w_{st}}{w_{gt}})$$

$$\frac{w_{st}}{w_{gt}} = \frac{\eta_{st} (1 - \eta_{gt})}{\eta_{gt}}$$

$$\eta_{gst} = \eta_{gt} + \eta_{st} (1 - \eta_{gt})$$
$$\eta_{gst} = \eta_{gt} + \eta_{st} - \eta_{st} \eta_{gt}$$
$$\eta_{gst} = \eta_{st} + \eta_{gt} (1 - \eta_{st})$$
$$\eta_{gst} = 1 - (1 - \eta_{gt})(1 - \eta_{st})$$

The notations are as follows:

η_{gt} thermal efficiency of gas turbine plant

η_{st} thermal efficiency of steam turbine plant

η_{gst} thermal efficiency of combined cycle plant

q_{gt} heat supplied to gas turbine plant

q_{st} heat supplied to steam turbine plant

w_{gt} shaft work by gas turbine plant

w_{st} shaft work by steam turbine plant (12)

Thermal efficiency of a power plant measures how effective it can convert heat energy into work which is then converted to electrical output. As such, it is an important measure for power plant. Also, an efficient system uses less fuel, thus incurring lower fuel cost and lower operating costs for the plant. (13)

12. S M Yahya, “Combined Cycle Plants”, *Turbines, Compressors and Fans*, (Tata McGraw-Hill Publishing Company Limited, 3rd ed), pp180-182
13. Woodruff and Lammers, p115

Advantages

A combined cycle power generation system offers many advantages.

As most combined cycle generation systems use natural gas as the fuel, the environmental emissions are low. There is less pollution produced compared to conventional steam or gas turbine power plants (14). As such, complex and expensive environmental control systems are not needed (15). Transportation of fuel via pipelines is also easier than that of coal and oil.

The gas turbine portion of the combined cycle system is easy to install. This means a short schedule of about 1 year from order to operation while the steam turbine portion can operate within another year (16). This can provide the grid with power earlier than with other systems.

The combined cycle power generation system also offers quick part-load starting. For example, the GE Model-7000 gas turbine is able to produce maximum output of 198MW within 30 minutes while the steam turbine portion takes about an hour to operate from a cold start. It can operate over a wide range of loads and is suitable for meeting peak power requirement and also base load (17). Supplementary firing can be used to increase steam turbine output in times of increased output demand. On the other hand, the gas turbine can be stopped when there is a decrease in demand (18).

14. Yahya, p185
15. Woodruff and Lammers, p114
16. Woodruff and Lammers, p112
17. El-Wakil, pp342, 347
18. Yahya, p184

It is also cheaper to build a combined cycle power plant than coal, nuclear or renewable energy power plant (19). Its capital cost is lower than that of steam turbine plant (20).

Disadvantages

The combined cycle power generation system is not without its disadvantages.

As natural gas is the fuel used, its higher cost compared to coal and oil will result in higher operating cost (21). The system is also less flexible with regards to the types of fuel to be used, thus this limit in resources means the supply of fuel is critical to the plant's operation (22).

Also, the combined cycle power generation system is a combination of two technologies, the complexity will result in higher maintenance cost (23) and also it will require highly skilled and better trained operating staffs (24).

The capital cost of a combined cycle power generation plant is higher than that of gas turbine plant (25).

19. Ann Chambers, *Power Primer, A Nontechnical Guide from Generation to End Use*, (PennWell Publishing Company), p47
20. Yahya, p185
21. Woodruff and Lammers, p112
22. Yahya, p185
23. Woodruff and Lammers, p114
24. Yahya, p185
25. Yahya, p185

Future

There are many power generation systems available in the world. Although nuclear power plants are clean and efficient, they are expensive and complex. They are also less easily accepted by the population due to the experience of the Three Mile Island and Chernobyl incidents. On the other hand, combined cycle power plants offer flexibility in terms of size and outputs, and are faster to build than nuclear power plants. The ability to increase and decrease output on demand gives combined cycle power plants an upper hand in the competitive power markets (26).

The Earth's supply of natural gas has been estimated to last 70-100 years (27), and as long as natural gas price remains low, combined cycle power generation will have the competitive edge against other forms of generation. Also, with advancement in technology, the capital cost of combined cycle generation has dropped from US$600/kW in 1990 to less than US$350/kW today (28).

Studies in the United Kingdom have also predicted that by 2050, 40 – 50% of UK's power supply will be dominated by combined cycle power plants (29).

From these, with continual improvement to the system, we can see that combined cycle power generation will become the mainstay in the power industry for at least the next few decades.

26. Malcolm C Grimston, "Nuclear energy", In *Future Electricity Technologies and Systems*, ed. Tooraj Jamasb *et al.*, pp199-200 (Cambridge University Press)
27. Chambers, p21
28. Chambers, p47
29. Ian Elders *et al.*, "Electricity network scenarios for the United Kingdom in 2050", In *Future Electricity Technologies and Systems*, ed. Jamasb *et al.*, p24, (Cambridge University Press)